Land-Atmosphere Exchanges Across the Midcontinental Region of North America: Processes, Scaling, and Evaluation

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Abstract

Observations of CO_2 fluxes by eddy covariance are an important source of process-level information, but flux towers provide only a very sparse sample of the heterogeneous mosaic of natural and managed ecosystems in the mid-continent US. Regional synthesis requires combining eddy covariance data with spatial information on management and soils, remote sensing, and modeling, and evaluation of models by comparing predictions to observed atmospheric CO_2 and agricultural yield.

The modeling and analysis project we propose will take place across a five-state region selected for the Mid-Continent Intensive (MCI) experiment of the North American Carbon Program (NACP).

We hypothesize that (1) seasonal variations in carbon flux over crops simulated by a land-surface model (SiB) will be substantially improved by inclusion of crop-specific phenology algorithms developed for crop production models; (2) the modified model will adequately reproduce variations in cropland carbon fluxes at several flux towers over different crops; and (3) when parameterized across the region and coupled to an atmospheric transport model, the system will predict regional agricultural yields and spatial and temporal variations in atmospheric CO_2 made during the NACP MCI experiment.

We propose to develop, implement, and evaluate a numerical modeling system to estimate time-varying exchanges of carbon, water, and energy across the NACP MCI region, using a coupled modeling system (SiB-RAMS) tested against observations at a variety of spatial scales. We will include the physiology and phenology of important agroecosystems in the region. Combining satellite imagery and several survey-based data sources, we will develop 1-km gridded datasets for vegetation cover, soils and management practices in the mid-continent region, and compare our simulations to observed fluxes and inventory measurements made during the NACP Mid-Continent Intensive experiment. After evaluating the improved offline model for specific sites, we will perform very high resolution simulations of Intensive Observing Periods using the fully coupled SiB-RAMS model. These simulations will be evaluated by comparing to airborne transects of eddy covariance measurements, atmospheric trace gas distributions, and cropland carbon inventory measurements made by other investigators involved in the MidContinent Experiment.

The proposed research is intended to evaluate a primary scaling strategy for the NACP. Deliverables will include regionally-gridded hourly fluxes, evaluation against regional crop production and atmospheric CO_2, and a modeling and analysis system, including model code and data, released through the NACP Data and Information System.

1. Introduction

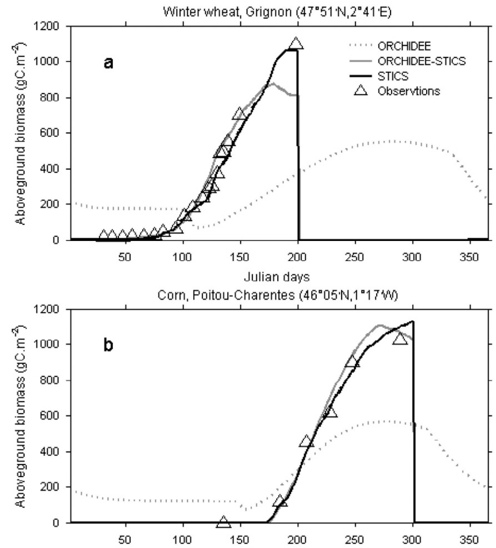

Figure 1: Seasonal cycles of aboveground biomass simulated in a biophysical model (ORCHIDEE, dotted lines), as modified by a crop model (STICS, heavy lines), and observed (triangles).
From de Noblet-Ducoudre et al (2004).

Uncertainty in the climate of the 21st century is driven by (1) uncertainty about future emissions of greenhouse gases; (2) uncertainties about the response of the physical climate system to enhanced greenhouse gas loading; and (3) uncertainties in biogeochemical responses to changing climate, atmospheric composition, and land use/ land management (IPCC, 2001). The land and ocean currently mitigate greenhouse gas loading by absorbing roughly one-half of the anthropogenic emissions of CO_2, but the biogeochemical sinks are not completely understood and most mechanistic hypotheses involve processes that are expected to saturate over coming decades. In this likely scenario, the growth rate of greenhouse gases would rise dramatically unless emissions were cut very aggressively.

To address uncertainties in the functioning of the carbon cycle under elevated CO_2, a changing climate, and shifting land management, US agencies have undertaken the North American Carbon Program (NACP, Wofsy and Harris, 2002; Denning et al, 2005). The NACP includes efforts to estimate spatial and temporal variations of carbon sources and sinks over North America by both extrapolation from surface data (bottom-up) and interpolation from atmospheric carbon gas measurements (top-down). Mechanistic source attribution, improved predictive models, and decision support resources are also major components of the program. A near-term priority for NACP is to evaluate the planned top-down/bottom-up synthesis of full carbon budgets over heavily managed landscapes in the agriculturally-dominated mid-continent region of the US. This so-called Mid-Continent Intensive (MCI) experiment is already underway and includes dozens of separate investigations which focus on measurements, experiments, and modeling in the region (http://www.nacarbon.org).

The strategy adopted for the MCI experiment involves collecting higher-density observations over this limited area for a limited time than is envisioned for the continental-scale observing system, so that carbon fluxes can be quantified and an optimally-configured observing and analysis system can be constructed. This "oversampling" approach includes measurement of atmospheric data continuously from a network of towers and episodically from aircraft; spatial data on soils, crops, wetlands, and forests; an enhancement to the network of ecosystem flux sites; and studies of the fate of organic carbon (e.g., grain and timber) transported off-site.

An important goal of the MCI is to test the ability of spatially-explicit models to simulate high-frequency variations of surface carbon exchange in this heavily managed and spatially-heterogeneous region. Although monthly or seasonal total changes in carbon storage may suffice for bottom-up inventories constructed from crop yields and spatial statistics, the top-down atmospheric constraint requires that changes in flux on diurnal to synoptic time scales be accounted for in the inverse models (Gerbig et al, 2003). Most biophysical models of land-atmosphere exchange suitable for this purpose include only a rudimentary description of crops, and are better suited for simulation of exchanges with “natural” vegetation such as forests and grasslands.

By coupling a terrestrial ecosystem and biophysical model to a classic crop yield model, a recent European study showed dramatic improvements in the representation of seasonal changes in leaf area and carbon uptake by crop species (Gervois et al, 2004, see Fig 1). The coupled model was much better at predicting surface heat and water fluxes, and atmospheric temperature and humidity than the standard model (de Noblet-Ducoudre et al, 2004). Although well-suited to estimating the timing of crop-specific phenological events and yields, crop models typically have only rudimentary treatments of hydrology, the surface energy budget, and radiation.

We propose to modify a state-of-the-art model of ecophysiology to treat crop-specific phenology and physiology. We plan to test the improved model against eddy-covariance data collected over agroecosystems. The model will be parameterized using spatial data being developed for the NACP. Finally, we plan to apply the new modeling system for synthesis of top-down and bottom-up measurements in the MCI experiment. The model we will modify is a new version of the Simple Biosphere model (SiB). It includes calculation of the surface energy budget, including separate treatment of direct and diffuse radiation, on a subhourly time step. Photosynthesis and transpiration are calculated from enzyme kinetics and stomatal physiology, and consider both C3 and C4 processes. It tracks soil moisture and root uptake in 10 soil layers, and has recently been modified to include allocation, litter production, and decomposition of organic pools. The model is fully coupled to a the Regional Atmospheric Modeling System (RAMS, a mesoscale weather model), which predicts weather and trace-gas transport on an arbitrarily fine nested grid. The coupled modeling system will be modified to include tillage, sowing, germination, growth, anthesis, grainfilling, harvest, and decomposition of crop residues. We will use the modified system to analyze finely resolved carbon fluxes at high time frequency, and evaluate it by comparison to atmospheric measurements collected in the Midcontinent Intensive Experiment.

2. Model Development

The Regional Atmospheric Modeling System (RAMS) is a mesoscale meteorological (non-hydrostatic) model and contains time-dependent equations for velocity, non-dimensional pressure perturbation, ice-liquid water potential temperature (Pielke et al, 1992), total water mixing ratio, and cloud microphysics. Vapor mixing ratio and potential temperature are diagnostic. A significant feature of the model is the incorporation of a telescoping nested-grid capability, which enables the simulation of phenomena involving a wide range of spatial scales (Walko et al, 1995). A second-order advection scheme is employed. The turbulence closure scheme of Deardorff (1980) is used, which employs a prognostic sub-grid turbulent kinetic energy. The two-stream radiation scheme developed by Harrington (2000) is used. At regional scales for which individual convective elements (clouds) cannot be resolved, we use convective parameterizations (Grell, 1993; Freitas et al, 2000) that compute precipitation rates, atmospheric heating and moistening, and mass and tracer fluxes (including updraft and downdraft velocities) by unresolved cloud processes. The lowest level above the surface in the RAMS model is the reference level at which atmospheric boundary layer values of temperature, vapor pressure, wind velocity and carbon dioxide partial pressure are calculated. Additionally, the direct and diffuse components of short wave and near infrared radiation incident at the surface are provided from the RAMS radiation scheme.

RAMS has recently been coupled to the Simple Biosphere Model (SiB), a land-surface parameterization scheme originally used to compute biophysical exchanges in climate models (Sellers et al, 1986), but later adapted to include ecosystem metabolism (Sellers et al., 1996a; Denning et al, 1996). The parameterization of photosynthetic carbon assimilation is linked to stomatal conductance and thence to the surface energy budget and atmospheric climate (Collatz et al., 1991, 1992; Sellers et al., 1996a; Randall et al, 1996; Sellers et al, 1997; Schaefer et al, 2002, 2005). The model has been updated to include prognostic calculation of temperature, moisture, and trace gases in the canopy air space and has been evaluated for multiyear simulations of a number of eddy covariance sites (Baker et al, 2003; Vidale and Stöckli, 2005). Other recent improvements include biogeochemical fractionation and recycling of stable carbon isotopes (Suits et al, 2004), improved treatment of soil hydrology and thermodynamics, and the introduction of a multilayer snow model based on the Community Land Model (Dai et al, 2003).

Direct-beam and diffuse solar radiation are treated separately for calculations of photosynthesis and transpiration of sunlit and shaded canopy fractions. An allocation and turnover scheme based on the CASA model has been implemented and tracks carbon storage in nine biogeochemical “pools.” The model is now referred to as SiB3. The atmospheric surface layer, between the vegetation and the lowest level of RAMS is incorporated as part of SiB and is based on the scheme of Holtslag and Boville (1993). The input variables provided by RAMS to SiB are updated every minute of simulation time. SiB returns to RAMS, at the reference level, fluxes of heat, moisture, momentum and carbon dioxide, as well as the upwelling radiation. The coupled SiB-RAMS model has been used to study PBL-scale interactions among carbon fluxes, turbulence, and CO_2 mixing ratio (Denning et al, 2003) and the regional-scale controls on CO_2 variations (Nicholls et al, 2004; Wang, 2005; Corbin, 2005).

Until recently, ecosystem respiration was treated in SiB by scaling a temperature and a moisture response to achieve net carbon balance at every grid cell in one year by prescribing the size of a single pool of organic matter. This approach has recently been replaced by a scheme for allocation, transformation, and decomposition based on the Carnegie/Ames/Stanford Approach (CASA, Randerson et al 1997). Stored photosynthate is allocated to leaves, stems, and roots in fractions that are constrained by changes in satellite vegetation index (NDVI). Carbon is tracked through biomass pools and released to the surface as dead litter, woody debris, and root litter, where it interacts with a microbial pool to produce several pools of soil organic matter and CO_2. The interactive biogeochemistry module has been tested at dozens of eddy covariance sites and found to improve simulations of the seasonal cycle of net ecosystem exchange relative to the single-pool model it replaces (Kevin Schaefer, unpublished simulations). Under separate support from NASA in collaboration with James Collatz, we also plan to add a fire module to this model.

Historically, SiB has used prescribed vegetation parameters derived by remote sensing (Sellers et al, 1996b). At global scales, this approach allows realistic simulation of spatial and temporal variations in vegetation cover and state (Denning et al, 1996; Schaefer et al, 2002, 2005). At the underlying pixel scale, however, phenology products derived from satellite data must be heavily smoothed to remove dropouts and artifacts introduced by frequent cloud cover. An inevitable trade-off between cloud-induced "noise" in the leaf area and time compositing systematically stretches the seasonal cycle by choosing data late in each compositing period in spring, and early in each composite in fall. Under separate support from NASA's Energy and Water System program, we are addressing this problem by developing and testing a prognostic phenology module for SiB (and for the Community Land Model, CLM). We are assimilating vegetation imagery into the prognostic phenology model to estimate its parameters (e.g., growing degree day thresholds), rather than forcing it with the satellite data.

Smoothed satellite-based phenology products, and diagnostic models derived from them are especially poorly suited for simulating agricultural crops, whose life cycle is determined by intentional management. For example, winter wheat is sown and germinates in autumn, so root and some shoot growth occurs during the late autumn months. The most rapid phase of growth is then in early spring, followed by anthesis (flowering) and grain-filling. Senescence and harvest occur in early summer while natural grasslands are still in the growth phase (see Fig 1). This dramatic shift of the seasonal phenology relative to natural C3 grasslands is evident in eddy covariance data collected over wheat fields, and the early senescence has been noted as a particular problem in SiB (Hanan et al. 2005). Maize cultivation follows a seasonal cycle more similar to native grasslands, but growth and grain-filling stages are very rapid, and rates of CO_2 uptake are much greater than native grasses or most other crops (Brye et al, 2002). Peak values of net ecosystem exchange (NEE) measured by eddy covariance over maize can exceed 40 μmol m^{-2} s^{-1}, and surface layer CO_2 mixing ratio has been measured as low as 305 ppm, nearly 80 ppm lower than background values (S. Verma, personal communication).

SiB currently simulates crops using a single "generic" set of parameters, but clearly fails to capture the early seasonal development and senescence of wheat or the very high rates of photosynthesis produced by maize. When coupled to a global atmospheric transport model, SiB can reproduce many aspects of seasonal, synoptic, and diurnal variations in atmospheric CO_2 observed at a very tall television tower (Fig 2). During periods when calculated back trajectories pass over extensive areas of corn agriculture to the south and west of the tower, the model typically fails to reproduce depressions of as much as 20 ppm in the observed CO_2. This "corn signal" in the atmospheric mixing ratio can be a valuable observational constraint in obtaining regionally-integrated fluxes in the MCI.

Other important aspects of the seasonal carbon cycle that require special treatment over crops relative to natural landscapes include tillage and harvest. Tillage may release large amounts of CO_2 to the atmosphere, and affects surface roughness and albedo. Harvest dramatically transforms the landscape in a very short period, removing much of the carbon, exposing the soil, and changing most of its physical characteristics on a time scale much faster than smoothed satellite products can resolve. These processes will be included in the revised version of SiB-RAMS.

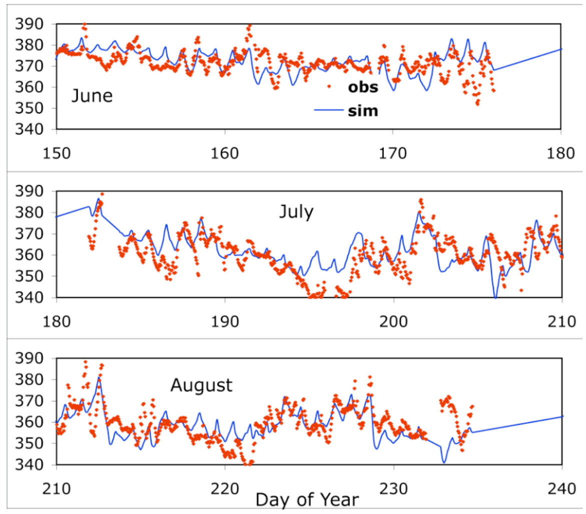

Figure 2: Simulated and observed variations in atmospheric [CO_2] at WLEF, summer 2002. Note probable "corn effect" in mid-July.

Agricultural landscapes in the US mid-continent region are a mosaic of adjacent fields of different crops, fallow fields, natural grass, suburban landscapes, and wetlands. This finely-expressed heterogeneity is a challenge to represent even in a mesoscale model, especially given the very strong variations in phenology and physiology described above. SiB-RAMS employs a "tiling" method to treat subgrid-scale variations in the land surface and their combined effect on the overlying atmosphere. Multiple instances of SiB are run in each atmospheric grid cell, each with its own vegetation, soil column with prognostic water distribution and temperature, rooting profile, and snowpack. The fluxes computed by each subgrid "tile" are passed to the atmospheric reference layer after area-weighted averaging.

SiB includes a detailed physiological-based photosynthesis and energy balance model and biomass partitioning functions adapted for native vegetation. To improve the representation of crop growth, we will adapt empirical relationships of crop-specific biomass partitioning as a function of phenological development, as used in many crop models (e.g. Jones et al. 2003, Ritchie and NeSmith 1991, Rickman and Klepper, 1991). Thermal time and photoperiod are typically used to model phenological development (i.e., germination, early and late vegetative stages, anthesis, grain-filling, maturity) of annual crops. Stress conditions have also been included as effects on partitioning (e.g. drought and grain-fill potential). Similarly, root distribution functions and species-specific maximum photosynthetic rates and leaf biomass/leaf area ratios will be derived from existing crop models (e.g. DSSAT system of crop models; Jones et al. 2003) and tested (in the stand-alone version of SiB) against time series of crop production data at long-term agronomic plots. We have compiled a database of agricultural experiments (Paul et al. 1997, Ogle et al. 2006) for which we have detailed records of management practices and long-term measurements of crop production and soil variables. These together with Ameriflux cropland sites in the MCI region will be used to test and validate the enhancements to the SiB model (see section 3 below).

Crop residue management and tillage functions will be incorporated into the present version of SiB using algorithms from the Century model (Parton et al. 1994). SiB presently employs a soil organic matter pool structure similar to Century. Incorporating tillage functions will control the depth and distribution of residue incorporation and the influence of tillage on SOM decomposition rates, using scaling functions that depend on the type of tillage implements used (Buyanovsky and Wagner, 1986; Campbell and Jong, 2001).

Crop management practices, including planting, fertilization and tillage, will be specified for the MCI region at the county-level, using databases which we have previously compiled for modeling greenhouse gas emissions for the US national inventory reporting (EPA, 2005). These include statistics on area by crop type, county-level tillage information compiled by the Conservation Technology Information Center (CTIC, 2006; from 1988 to present), fertilizer use by crop (ERS, 2006) and cropping calendars compiled by the Joint Agricultural Weather Facility (NOAA/ USDA) and National Agricultural Statistics Service. The management practices represented for each of the major crops (corn, soybean, wheat, hay) used in the crop "tiles" within a SiB-RAMS gridpoint will be taken from the dominant practice within the county containing that grid cell.

3. Development and Testing at Local Scales

The improved model will be developed and tested offline of RAMS at specific eddy covariance sites located in agricultural systems. We have identified 12 such sites in the mid-continent region with multiple years of data (Table 1). As much as possible, the

Table 1: Eddy Covariance Sites to be Used for Model Development and Parameterization

Site Name	Lat	Lon	Crop	PI	Start
Bondville, Illinois	40° 0' 21.96" N	88° 17' 30.72" W	Corn-soybean	Tilden Meyers, NOAA, ARL	Aug 1996
Bondville, Illinois (companion site)	40° 0' 21.96" N	88° 17' 30.72" W	Corn-soybean	Steven Hollinger & Carl Bernacchi, IL State Water Survey	2002
Fermi National Accelerator Laboratory, Batavia, Illinois	41° 51' 33.48" N	88° 13' 21.84" W	Corn-soybean	Roser Matamala & David Cook of Argonne NL	2005
Brooks Field Site 10, Ames, Iowa	41° 41' 29.33" N	93° 41' 28.99" W	Corn-soybean	Tim Parkin, USDA	2002
Brooks Field Site 1011, Ames, Iowa	41° 58' 32.35" N	93° 41' 33.07" W	Corn-soybean	Tim Parkin, USDA	2002
Brooks Field Site 11, Ames, Iowa	41° 58' 28.99" N	93° 41' 36.86" W	Corn-soybean	Tim Parkin, USDA	2002
Neal Smith Prairie, Ames, Iowa	41° 33' 28.37" N	93° 17' 46.27" W	Corn-soybean	Tim Parkin, USDA	2002
Kellogg Biological Station, SW Michigan	42° 4' 36.29" N	85° 2' 32.4" W	alfalfa	Jiquan Chen, Univ. of Toledo	1988
Rosemount, G21, Minnesota	44° 42' 45.60" N	93° 5' 36.24" W	Corn-soybean	Timothy Griffis, Univ. of Minnesota, John Baker, USDA ARS	2004
Mead (1) - irrigated Nebraska	41° 9' 54.20" N	96° 28' 35.90" W	Maize	Shashi Verma & others, UNL	Spring 2001
Mead (2) - irrigated, Nebraska	41° 9' 53.54" N	96° 28' 12.36" W	Corn-soybean	Shashi Verma & others, UNL	Spring 2001
Mead (3)- rainfed, Nebraska	41° 10' 46.80" N	96° 26' 22.73" W	Corn-soybean	Shashi Verma & others, UNL	Spring 2001

model will be parameterized from local data for each site and driven by surface weather obtained from meteorological reanalysis (as was done with earlier versions of SiB by Schaefer et al, 2002 and Baker et al, 2003, for example). The advantage of offline development and testing is that the model runs very fast in this configuration, so that many runs can be completed while testing various algorithms and parameter sets. Actual dates of tillage and planting, soil hydraulic properties, and soil carbon data will be used in the model.

The first experiments will concentrate on evaluation of the new phenology module derived from the DSSAT system of crop models (Jones et al, 2003). We will evaluate simulated leaf area index and the timing of flowering, grainfilling, and predicted harvest dates against actual dates. We will then focus on seasonal cycles of simulated fluxes of sensible and latent heat (H, LE) and net ecosystem exchange (NEE) of carbon dioxide by comparing them to the eddy covariance measurements. Comparison of the simulated versus observed mean diurnal cycle can reveal incorrect specification off canopy radiative transfer or stomatal response to high mid-day radiation loads. Day-to-day variations in response to passing weather disturbances are important as they relate to response to direct *vs* diffuse light and variations in soil moisture. We will pay special attention to the corn-soybean rotation sites, because interannual variations there allow evaluation of the treatment of different crops for the same soil.

While our primary focus in this research is investigating diurnal, synoptic, seasonal, and interannual CO_2 fluxes and concentrations, we will also improve the treatment of soil carbon processes in SiB. A special consideration for these sites is the model's ability to simulate post-harvest respiration and decomposition of crop residues. To test these aspects of the model, we will decrement the model's biomass pools upon harvest, and focus carefully on diurnal and seasonal changes in simulated and observed NEE over the following months. We have compiled over 45 long-term field experiments with over 800 treatments (Ogle et al. 2006) in which soil C was measured under a variety of management conditions (e.g., variation in crop rotation, tillage, fertilization rates, manure amendments). We will use crop production and soil carbon data from these sites to help set allocation and soil carbon turnover parameters in the model.

At this initial stage of the project, we do not expect excellent performance, but rather will adjust parameters and process representations as necessary to obtain a satisfactory result for each site. Model evaluation will be performed later, using regional data (see section 5 below).

4. Regional Parameterization and Spatial Statistics

Spatially distributed variables of soils and crop management schedules and practices will be included as drivers for SiB-RAMS. A 30-m gridded crop landcover product, based on an integration of Landsat imagery and NASS data is being developed as part of ongoing NACP research (T. West, pers. comm., see attached letter of support). The 30-m landcover will be overlain with the RAMS grid to derive the area-weighting of sub-grid tiles by crop type. County-level data on crop management practices, including planting, fertilization and tillage, have been combined in previous work on modeling greenhouse gas emissions for the US national inventory reporting (EPA, 2005). These include statistics on area by crop type, county-level tillage information compiled by the Conservation Technology Information Center (CTIC, 1998; from 1988 to present), fertilizer use by crop (ERS, 2003) and cropping calendars compiled by the Joint Agricultural Weather Facility (NOAA/ USDA) and National Agricultural Statistics Service. The management practices represented for each of the major crops (corn, soybean, wheat, hay), used in the crop "tiles" within a SiB-RAMS gridpoint, will be taken from the dominant practice within the county. Data on soil physical properties will be extracted from USDA's STATSGO soils data, which is a contiguous spatial database for the entire US, consisting of vector-based soil associations at 1:250,000. The 1 km grid will be overlain on the STATSGO coverage and the attributes of the dominant soil series within the association making up the largest fraction of the grid cell will be used in the model (most grid cells will contain a single soil association).

County-level crop productivity estimates, based on annual surveys conducted by the National Agricultural Statistics Service

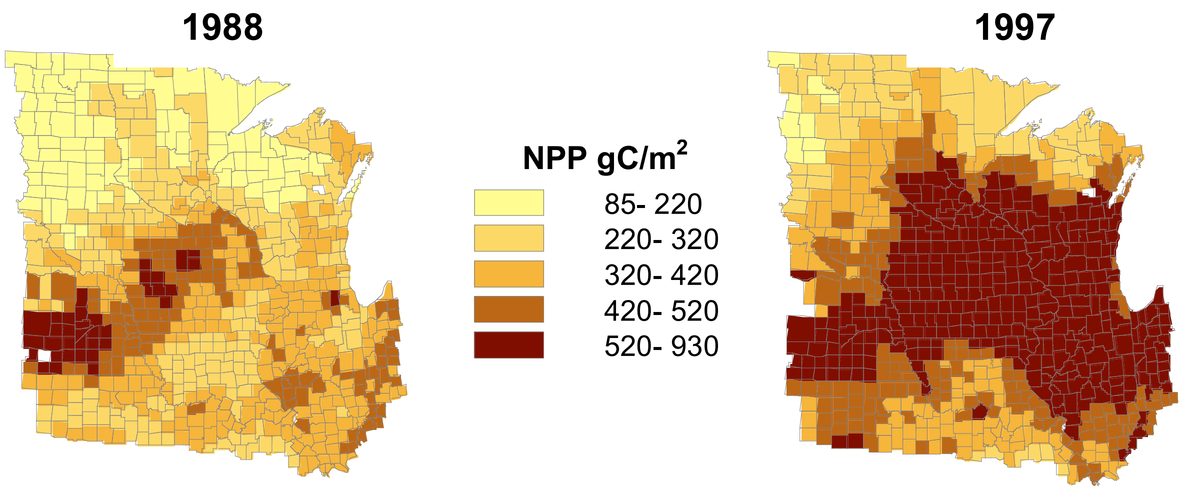

Figure 3: Cropland NPP in the mid continent region during a dry year (1988) and a wet year (1997)

(NASS) and the Census of Agriculture (Ag Census; data reported every 5 years) provide an independent "ground-truth" estimate of net primary production from agricultural crops (Fig. 3). These data provide useful constraints for total crop NPP in the region as well as a measure of the historical interannual variability in cropland NPP in the region. In previous work, we developed statistical models incorporating climate, management and economic data to combine NASS and Ag Census data and fill data gaps, to create a complete, contiguous observation set of crop yields (1982-1997). Allometric relations were derived from more than 100 published studies to relate reported yields to above- and below-ground NPP (Williams and Paustian, in prep). As part of this project, we propose to update the crop NPP database to the most recent reporting year (2008 by the end of this project), to serve as a spatially-integrated comparison data set for the model NPP estimates.

5. Evaluation in Regional Coupled Ecosystem-Atmosphere Model

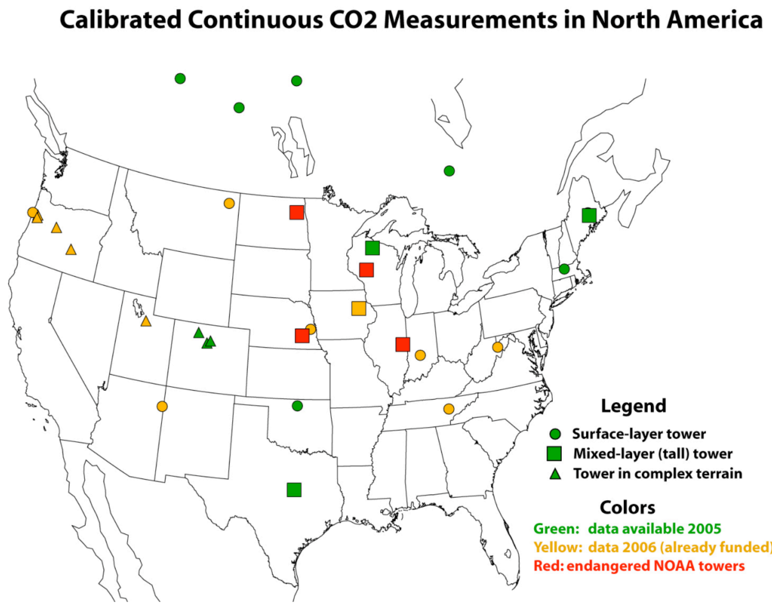

Figure 4: Locations of calibrated CO_2 measurements

The NACP Mid-Continent Intensive experiment will provide an excellent opportunity to evaluate the improved representation of croplands in SiB. An augmented network of eddy covariance sites in the region will provide additional flux data for sites at which the model was not calibrated. Detailed compilations of regional production data will be undertaken by a number of bottom-up synthesis studies, and seasonal statistics can be compared quantitatively between the model and data-based estimates.

Unlike other bottom-up models, the availability of the coupled SiB-RAMS model allows us to test the regional patterns of variability by simulating the effects of NEE by agricultural and other ecosystems on the atmospheric CO_2, and comparing with a wealth of new observations that are planned for the MCI. Highly-calibrated continuous measurements of the mixing ratio of CO_2 are available from tall towers operated by NOAA as well as from a growing network of flux towers and other sites in the atmospheric surface layer (Fig 4). Variations in atmospheric CO_2 contain information about regional carbon exchanges at larger scales than the information from flux towers, because the air passes over large areas and integrates the effects of exchanges with a variety of surfaces (Gloor et al, 2001). Variations of CO_2 over periods of several days of as much as several 10's of ppm reflect different areas of upstream influence with different surface exchanges. The periodic summer drawdown events at WLEF associated with airmasses passing over the corn belt are one example (Fig 2), and the persistent springtime drawdown observed over Oklahoma during the growth phase of winter wheat is another (Marc Fischer, personal communication, not shown). During the MCI, additional mixing ratio measurements are being proposed by several investigators (see attached letters of support from Arlyn Andrews, Kenneth Davis and Steven Wofsy), from both towers and aircraft. In addition, airborne eddy covariance measurements of fluxes are being proposed by at least two groups (see attached letter of support from Paul Shepson).

We propose to carry out forward coupled simulations of the land-atmosphere exchanges, atmospheric transport and mixing ratio of CO_2 during the period of the MCI, using bottom-up data as well as atmospheric mixing ratios for model evaluation. The spatial domain will include all of the contiguous USA and parts of Canada, Mexico, and adjacent oceans. The continental model will be run on a 40 km grid, nested to 10 km over the MCI region. We will consult with our collaborators and the MCI Task Force to define Intensive Observing Periods during which additional data (e.g., airborne measurements) will be made. During these periods, we will perform much higher resolution experiments by adding nested a 2 km and 0.5 km grids in the center of the domain. The exact grid configurations, locations, and timing of these cloud-resolving experiments will depend on which other MCI investigations are funded, and will be made in collaboration with the rest of the MCI science team.

The coarse grid simulations will include multiple subgrid-scale "tiles" in each RAMS column, with different instances of SiB running in each one. These will be defined differently in different parts of the continental scale domain, but in the MCI region we will include tiles in each 10 km grid cell for maize, wheat, soybeans, fallow ground, forest, wetland, and suburban landscapes. Fractional cover of each of these tiles will be determined from the 1-km data products being developed by collaborators on the NACP Science Team (see attached letters of support). The model will be initialized by running the land-surface model offline for several years, forced by reanalysis weather, as was recently done globally by Schaefer et al (2002, 2005).

Simulated variations in atmospheric mixing ratios of CO_2 will be compared to calibrated continuous observations made at about 30 locations over North America (Fig 4). These include the network of tall tower measurements managed by the NOAA Environmental Science Research Laboratory, Global Monitoring Division (formerly CMDL). Plans to deploy five additional tall towers in the MCI region have been jeopardized by NOAA budget cuts (P. Tans, personal comm.), but there are also additional calibrated measurements being made by many investigators at flux towers and communications towers in the region (K. Davis, personal comm.). Lagrangian particle dispersion modeling will be used with SiB-RAMS output to trace airmasses backward in time in order to identify areas or times during which regional fluxes are less compatible with the observations (e.g., Gerbig et al, 2003).

Eddy covariance measurements made from aircraft can be used to map spatial variations in fluxes at high resolution, though only for brief periods. If airborne flux measurements are included in the MCI experiment, we will work with these investigators to coordinate high-resolution simulations with their campaigns, and to quantitatively compare our results with theirs.

Finally, very intensive measurements of atmospheric mixing ratio by instrumented jet aircraft are being proposed by a group led by Prof. Steven Wofsy at Harvard, over an area stretching from Wyoming to Oklahoma to Ohio. The measurements would be structured to follow airmass trajectories, would include vertical profiling, and would be made at much higher density in the MCI region than further upstream. These measurements are designed to quantify regional fluxes by inverse modeling. We are not proposing to perform inverse modeling here, though we are supported under a NASA Cooperative Agreement to perform such analyses at continental scales. Rather, we would target cloud-resolving nested simulations to match the dates on which the Harvard group would fly, and their data would be an excellent and rigorous test for our forward model of the weather, surface fluxes, and atmospheric transport.

6. Important Note on the Collaborative Nature of the Proposed Research

The research we propose here is extremely ambitious in scope, as is the entire North American carbon Program, but the budget is very limited. The only way NACP's ambitious objectives can be met is by strong collaboration and self-organization among the hundreds of separate science investigations that comprise it. Unlike previous regional experiments (FIFE, BOREAS, or LBA) or continental-scale programs in other countries (e.g., CarbonEurope), NACP has no single-agency budget, set of requirements, or program manager. The success of the entire program depends on all of us to talk to each other, plan together, coordinate measurements, modeling, and analysis, and aggressively share our results. It is in that spirit that we have organized this "tip of the iceberg" proposal. The greater part of the work that will make regional synthesis possible for the NACP MCI experiment will be conducted by dozens of other investigators, and funding is not solicited here for their work.

We hope to obtain site-specific data on soils, crops, management, and fluxes from Dr. Tilden Myers at NOAA, Dr. Tim Parkin at USDA, and Prof. Shashi Verma at the University of Nebraska. We pledge to seek collaborations from the other investigators listed on Table 1 as well. In exchange, we will offer model code and simulation results at the ecosystem scale, and work with these investigators to compare the simulations to the data and to analyze the strengths and weaknesses of the model. We anticipate sharing authorship on resulting papers as appropriate.

Model development work will be conducted in collaboration with Dr. Joe Berry (Carnegie Institution of Washington) and Prof. Chris Still (University of California, Santa Barbara), who are experts on plant physiology, C3 vs C4 photosynthesis, and stable isotope biogeochemistry. They are also submitting a proposal to improve the treatment and spatial distribution of C3 and C4 crops in SiB, and we plan to work closely with their project if we are both funded. We will share our spatial data products (e.g., crop maps), and they will share their insights about representing physiology at grid scale.

For spatial scaling of the ecosystem model to the region, we seek data being generated and collated by the research projects of Dr. Tristram West at Oak Ridge National Laboratory and Dr. Stephen Ogle at Colorado State University. In return, we will propagate the information from these projects into the overlying atmosphere, so that the spatial data they collate can be compared to observations made by others. We offer all of our data, model code, and results in the hope that they will be of help. We expect that these colleagues will be coauthors on our papers.

For evaluation of the coupled SiB-RAMS simulations against atmospheric data, we need to collaborate vigorously with colleagues that measure atmospheric fluxes and mixing ratios of CO_2. We have solicited letters of collaboration from Dr. Arlyn Andrews at NOAA ESRL, whose group measures CO_2 at a network of tall towers, and with Prof. Ken Davis at Penn State, who measures calibrated CO_2 on shorter flux towers, and is proposing to do so at more sites in the region. In addition, we plan to collaborate with Prof. Paul Shepson at Purdue, who plans to make airborne eddy covariance measurements as part of the MCI experiment. Finally, we have been in contact with Prof. Steven Wofsy at Harvard, who has proposed regional campaigns with an instrumented jet aircraft. In all of these cases for which funding is obtained, we will work closely with these colleagues to coordinate our modeling with their measurements, and vice versa. We hope to add value to each others' efforts, and would certainly share authorship on papers resulting from the regional synthesis work.

Letters of support and collaboration from each of these investigators are attached.

7. Relationship of Proposed Research to Other Denning DOE Projects

DOE Terrestrial Carbon Program: *Regional Ecosystem-Atmosphere CO_2 Exchange via Atmospheric Budgets* (ends 9/14/2006)

In this project, Denning collaborated with Ken Davis, Scot Richardson, and Natasha Miles at Penn State. They built and deployed six relatively inexpensive systems for making calibrated measurements of CO_2 mixing ratio at a "Ring of Towers" deployed about 200 km radius around the WLEF tall tower. We developed a method for estimating fluxes on a 20-km grid inside the ring, using a Lagrangian Particle Dispersion Model driven by output from RAMS. The current proposal is quite different because here we focus on evaluating a forward model after modifying it to simulate crop physiology and phenology, whereas in the Ring of Towers project the focus was on a specific field experiment including building and deploying instruments, then analyzing the results. That project will be finished before the new one is funded.

DOE Terrestrial Carbon Program: *Multi-year Regional Syntheses of Atmospheric Flux and Mixing Ratio Measurements in Support of the North American Carbon Program*

Denning will be a Co-Investigator on this **proposal to be submitted next week** with Ken Davis at Pennsylvania State University. In collaboration with Dr. Britt Stephens (NCAR), we will propose to build new and deploy existing instrument packages to make highly calibrated measurements of atmospheric CO_2 at a network of flux towers and communications towers in support of the NACP MCI. If we are funded, Denning's group would investigate spatial and temporal covariance patterns in GPP and ecosystem respiration across the MCI region using SiB-RAMS and eddy covariance towers. We are already funded by NASA to do continental-scale inverse modeling and data assimilation of concentration data in SiB-RAMS. The DOE project would focus on the flux covariance problem, which is a key to obtaining unbiased estimates of the fluxes by inversion. We would also perform high-resolution inversions of the new tower data proposed to TCP. The research proposed here to NICCR is very different from the TCP proposal. Here we focus on major modifications to the process representations in SiB (adding explicit treatment of agricultural management and crop physiology) and evaluate forward simulations. For TCP we focus on making CO_2 measurements and then performing regional flux estimation from them by inverse modeling.

DOE Terrestrial Carbon Program: *A Multiyear Reanalysis of North American Regional Carbon Exchange from a Synthesis of AmeriFlux Eddy-covariance and Atmospheric Mixing Ratio Observations*

Denning will be a Co-Investigator on this **proposal to be submitted next week** with Dr. Wouter Peters at the University of Colorado. Weather and satellite data will be fed to SiB in near-real time to calculate fluxes to the TM5 model, which will make maps of daily CO_2 variations on a publicly-accessible web site. Discrepancies between simulated and observed CO_2 will be attributed to fluxes on a weekly basis in "ecoregions" defined by Forrest Hoffmann and Bill Hargrove, based on Ensemble Kalman Filter analysis with TM5. Ameriflux data will be used to parameterize SiB for each ecoregion. The current proposal focuses on forward modeling of crops. The TCP proposal focuses on near-real time forecasts and inversions using a global model.

8. Schedule and Deliverables

- *Year 1: Model development and testing at local sites.*

We will obtain eddy covariance data, as well as local site data on cropping and tillage practices, soils, nutrients, and yields, from our partners (see attached letters of support). We will modify SiB3 to read information from files and compute phenological dates for specific crops. We will modify the allocation logic in SiB to accommodate additional pools (flowers, grains), and to respond to the crop phenology. We will run the model for multiple crop sites in multiple years, and analyze the results.

We will deliver site simulations and model code to our collaborators and to the community via the NACP Data and Information System, which is currently being designed and competed.

- *Year 2: Development of spatial databases, coupling to RAMS, initialization and offline spinup*

We will couple the new version of SiB to RAMS. We will obtain spatial data on crop coverage and soils, and aggregate onto the continental (40 km) and regional (10 km) grid to be used in SiB-RAMS, using the subgrid-scale tiling feature in RAMS. We will run a multiyear "spinup" of SiB on the RAMS grid, to initialize soil moisture and carbon storage fields.

We will work closely with our collaborators (see attached letters of support) to define Intensive Observing Periods for the NACP MCI experiment, and to organize our efforts to produce high-resolution nested simulations of these IOPs. Publish papers on work from year 1.

We will deliver site simulations and model code to our collaborators and to the community via the NACP Data and Information System, which is currently being designed and competed. These will be huge data sets, because they will include the 3D atmosphere on hourly time scales.

- *Year 3: Coupled 1-km simulation of weather, fluxes, allocation, pools, and atmospheric CO_2 during MCI IOPs.*

We will perform nested grid simulations down to sub-km scales of brief (e.g., 2 week) periods during which intensive observations were collected for the MCI experiment. We will compare our results in detail to eddy covariance data collected on towers and from low-flying aircraft, to mixing ratios of atmospheric CO_2 measured from towers and aircraft, and to agricultural production data collected by USDA.

We will present our results at meetings, publish papers on them, and use them to help design future experiments in the NACP and beyond. We will deliver vast amounts of data to the community through the NACP Data and Information System.

9. Results from Previous NIGEC Support

Scott Denning, P. I.

Regional Estimation of Terrestrial CO_2 Exchange from NIGEC flux Data, Satellite Imagery, and Atmospheric Composition

South-Central Regional Center: 1998-2002

This investigation sought to bridge the gap between detailed eddy flux measurements made at local scales (for which regional representativeness is difficult to establish) and regional information provided by inversion studies (whose results are difficult to apply to particular ecosystems because of their coarse resolution). Inverting atmospheric observations using simulated tracer transport over vegetated land surfaces requires careful evaluation of interactions among surface energy budgets, ecosystem carbon flux, and atmospheric turbulence and convection (the "rectifier effect") which can confound the inversion procedure: we sought to evaluate this effect in nature and in a series of models. Technical and financial obstacles preclude a flux network of sufficient density to resolve sub-regional spatial patterns in carbon flux: we worked to develop a testable method for extrapolation of these fluxes using modeling, remote sensing, and atmospheric data.

We coupled a self-consistent model (SiB2) of biophysical and biogeochemical exchanges at the land surface to local-scale turbulence models, to a mesoscale model, and to an atmospheric GCM. Vegetation was parameterized according to satellite imagery, and the models predicted observable quantities such as energy fluxes and CO_2 concentrations. The coupled models were quite successful at predicting variations of latent and sensible heat fluxes, CO_2 fluxes, and CO_2 concentrations at multiple spatial scales. Simulations at the regional scale were used to design sampling strategies for testing "bottom-up" estimates of fluxes using concentration measurements made from aircraft and tall towers.

Objectives:

- Extrapolate the carbon flux measurements made at three NIGEC-supported AmeriFlux towers to the scale of single GCM grid cells (10^5 km^2) using remotely sensed vegetation data and gridded weather analyses to drive the improved biophysical model coupled to a mesoscale atmospheric model (RAMS).
- Evaluate the realism and spatial scaling of the CO_2 "rectifier effect" over forests, grasslands, and croplands by using a hierarchy of simulations at multiple spatial scales to analyze simultaneous continuous measurements of surface carbon flux and the structure of the PBL over diurnal, synoptic, and seasonal time scales.
- Test several methods for estimation of area-averaged carbon exchange from concentration data, using "pseudodata" generated by the modeling system.

We published 8 papers in the peer-reviewed literature arising from research supported under this project. (See Annotated Bibliography below for details).

Keith Paustian, P. I.

Agroecosystem Boundaries and C Dynamics with Global Change in the Central United States

NIGEC – Great Plains Regional Center (1999-2001)

In previous NIGEC-funded research (in collaboration with J. Antle, S. Capalbo, S. Mooney and E.T. Elliott) 'Agroecosystem Boundaries and C Dynamics with Global Change in the Central United States' (1999-2001), we developed a regional modeling capability to assess climate change impacts on agroecosystems in the Central US. We developed a coupled ecosystem-economic model to test the hypothesis that farmers, by reacting to changes in profitability, driven by crop yield (and soil organic matter/fertility) responses to climate change, would change management and cropping systems and thereby significantly influence the impacts of climate change on cropland ecosystems.

The central findings of the research were the key role of changes in land use and management in mitigating the impacts of projected climate and CO_2 changes on soil C stocks, at both subregional and regional scales. With current distribution of land use and cropping systems, climate change tended to diminish soil C stocks in many areas, although losses were dampened by enhanced CO_2 effects on crop productivity. Changes in the spatial extent and distribution of cropping systems, driven by the economic decisions by farmers to climate induced changes in crop yields, reduced and in many cases reversed losses of soil carbon, compared to the non-adaptive scenarios.

The linked ecosystem-economic model was also used to evaluate climate change mitigation, through terrestrial carbon sequestration, in the Northern Great Plains. Soil carbon sequestration potential, through changes in land use and management, were quantified and farmer adoption rates of C sequestering practices were projected as a function of carbon payments. Incentive structures, as per hectare or per tonne payments, were evaluated and the relative advantage of different payment types was shown to vary as a function of spatial heterogeneity of soils and crop productivity and spatial scale. Results of the analyses were used to estimate costs of measurement and monitoring of soil C sequestration projects.

We published 13 papers in the peer-reviewed literature arising from research supported under this project. (See Annotated Bibliography below for details).

10. Literature Cited

Baker, I.T., A.S. Denning, N. Hanan, L. Prihodko, P.-L. Vidale, K. Davis and P. Bakwin, 2001: Simulated and observed fluxes of sensible and latent heat and CO_2 at the WLEF-TV Tower using SiB2.5. *Global Change Biology*, **9**, 1262-1277.

Brye, K. R., S. T. Gower, J. M. Norman, and L. G. Bundy, 2002. Carbon budgets for a prairie and agroecosystems: Effects of land use and interannual variability. *Ecological Applications*, **12(4)**, 962–979.

Buyanovsky, G.A., Wagner, G.H., 1986. Post-harvest residue input to cropland. *Plant Soil* **93**, 57- 65

Campbell, C.A., Jong, R. de. , 2001. Root-to-straw ratios- influence of moisture and rate of N fertilizer. *Can. J. of Soil Sci*. **81(1)**, 39- 43.

Collatz, G. J., Ball, J. T., Grivet, C. and Berry, J. A., 1991. Physiological and environmental regulation of stomatal conductance, photosynthesis, and transpiration: a model that includes a laminar boundary layer. *Agric. and Forest Meteorol*., **54**, 107-136.

Collatz, G. J., Ribas-Carbo, M. and Berry, J. A., 1992. Coupled photosynthesis-stomatal conductance model for leaves of C_4 plants. *Aust. J. Plant Physiol*., **19**, 519-538.

Corbin, 2005 *Evaluating Spatial, Temporal, and Clear-Sky Errors in Satellite* CO_2 *Measurements*. M. S. Thesis, Department of Atmospheric Sciecne, Colorado State University, 183 pp.

CTIC, 2006. National Crop Residue Management Survey. Conservation Technology Information Center [Online]. Available at http://www.ctic.purdue.edu/CTIC/CRM.html (accessed 07 March, 2006; verified 09 March, 2006).

Dai, Y., X. Zeng, R.E. Dickinson, I. Baker, G. Bonan, M. Bosilovich, S. Denning, P. Dirmeyer, P. Houser, G. Niu, K. Oleson, A. Schlosser and Z.-L. Yang, 2003: The common land model (CLM). *Bulletin of the American Meteorological Society*, **84**, 1013–1023.

Deardorff, J. W., 1980: Stratocumulus-capped mixed layers derived from a three-dimensional model. *Bound.-Layer Meteorol.,* **18,** 495-527.

Denning, A.S. et al, 1996: Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model. Part 1: Surface carbon fluxes. *Tellus*, **48B**, 521-542.

Denning, A.S., et al, 2003: Simulated and observed variations in atmospheric CO_2 over a Wisconsin forest using a coupled Ecosystem-Atmosphere Model.. *Global Change Biology*, **9**, 1241-1250.

Denning, A. S., 2005. *Science Implementation Strategy for the North American Carbon Program.* US Climate Change Science Program. Available online at http://CarbonCycleScience.gov.

de Noblet-Ducoudre, N., S. Gervois, P. Ciais, N. Viovy, N. Brisson, B. Seguin, and A. Perrier, 2004. Coupling the soil-vegetation-atmosphere-transfer scheme ORCHIDEE to the agronomy model STICS to study the influence of croplands on the European carbon and water budgets. *Agronomie* **24**, 1–11.

EPA 2005. Inventory of U.S. greenhouse gas emissions and sinks: 19902003. EPA 430-R-03-004. U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, D.C.

ERS, 2006. Ag Chemicals and Production Technology. Economic Research Service. [Online]. Available at www. ers.usda.gov (accessed 07 March, 2006; verified 09 March, 2006) USDA.

Freitas, S. R. et al, 2000. Modeling the convective transport of trace gases by deep and moist convection. *Hybrid Methods in Engineering*, **2**, 317-330.

Gerbig, C., J.C. Lin, S.C. Wofsy, B.C. Daube, et al., Toward constraining regional-scale fluxes of CO2 with atmospheric observations over a continent: 2. Analysis of COBRA data using a receptor-oriented framework, *J. Geophys. Res.*, **108(D24)**, 4757, doi:10.1029/2003JD003770, 2003.

Gervois, S., N. de Noblet-Ducoudre, N. Viovy, P. Ciais, N. Brisson, B. Seguin, and A. Perrier, 2004. Including croplands in a global biosphere model: Methodology and evaluation at specific sites. *Earth Interactions*, **8**, (16), 1-25.

Gloor, M., P. Bakwin, D. Hurst, L. Lock, R. Draxler, and P. Tans (2001), What is the concentration footprint of a tall tower?, *J. Geophys. Res.*, *106*(D16), 17,831–17,840.

Grell, G. 1993. Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Wea. Rev*, **121**, 764-787.

Hanan, N. P., J. A. Berry, S. B. Verma, E. A. Walter-Shea, A. E. Suyker, G. G. Burba, and A. S. Denning, 2004. Model analyses of biosphere-atmosphere exchanges of CO_2, water and energy in Great Plains tallgrass prairie and wheat ecosystems. *Agricultural and Forest Meteorology*, **131**, 162-179.

Harrington, J. Y., G. Feingold, and W. R. Cotton (2000), Radiative impacts on the growth of a population of drops within simulated summertime arctic stratus, *J. Atmos. Sci.*, **57**, 766-785.

Holtslag, A. A. M. and B. A. Boville (1993), Local versus nonlocal boundary-layer diffusion in a global climate model, *J. Clim.*, **6**, 1825-1842.

IPCC (2001) *Climate Change 2001: The Scientific Basis*. A Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.

Jones, C.A., Kiniry, J.R. 1986. Ceres-N Maize: a simulation model of maize growth and development, Texas A&M University Press, College Station, Temple, TX.

Jones, J.W., G. Hoogenboom, C.H. Potter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens, U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. The DSSAT cropping cropping system model. *Europ. J. Agron.* **18**(3&4), 235- 265.

Nicholls, M.E., A.S. Denning, L. Prihodko, P.-L. Vidale, K. Davis, P. Bakwin, 2004: A multiple-scale simulation of variations in atmospheric carbon dioxide using a coupled biosphere-atmospheric model. *Journal of Geophysical Research,* **109**, D18117, doi:10.1029/2003JD004482.

Ogle, S.M., F.J. Breidt and K. Paustian. 2006. Bias and variance in model results due to spatial scaling of measurements for parameterization in regional assessments. *Global Change Biology* (in press).

Paul, E. A., K. A. Paustian, E. T. Elliot, and C. V. Cole, eds. 1997. *Soil Organic Matter in Temperate Ecosystems: Long-Term Experiments in North America*. Lewis CRC Publishers, Boca Raton, Florida, USA.

Pielke, R. A. et al, 1992. A comprehensive meteorological modeling system - RAMS. *Meteor. Atmos. Phys.*, **49**, 69-91.

Parton, W. J., Schimel, D. S., Ojima, D. S., and C.V. Cole, 1994. A General Model for Soil Organic Matter Dynamics: Sensitivity to Litter Chemistry, Texture and Management', in Bryant, R. B. and Arnold, R. W. (eds.), *Quantitative Modeling of Soil Forming Processes*, SSSA Special Publication Number 39, Soil Science Society of America, Madison, WI, pp. 147–167.

Randall, D.R., P.J. Sellers, J.A. Berry, D.A. Dazlich, C. Zhang, J.A. Collatz, A.S. Denning, S.O. Los, C.B. Field, I. Fung, C.O. Justice and C.J. Tucker, 1996: Revised land-surface parameterization (SiB2) for GCMs, Part 3: The greening of the Colorado State University General Circulation Model. *Journal of Climate,* **9**, 738-763.

Randerson, J. T., M. V. Thompson, T. J. Conway, I. Y. Fung, and C. B. Field (1997), The contribution of terrestrial sources and sinks to trends in the seasonal cycle of atmospheric carbon dioxide, *Global Biogeochem. Cycles*, **11**, 535 – 560.

Rickman, R. W. and B. Klepper, 1991. Environmentally driven cereal crop growth models. *Annu. Rev. Phytopathol.* **29**, 361-380.

Ritchie, J.T. and D.S. NeSmith. 1991. Temperature and crop development. *In*: Hanks, R.J., Ritchie, J.T. (Eds), *Modelling Plant and Soil Systems*. Agronomy Monograph 31, American Society of Agronomy, Madison, Wisonconsin, pp. 5- 29.

Schaefer, K., A.S. Denning, N. Suits, Joerg Kaduk, I. Baker, S. Los, and L. Prihodko, 2002: The effect of climate on inter-annual variability of terrestrial CO_2 fluxes. *Global Biogeochemical Cycles,* **16**, 1102, doi:10.1029/2002GB001928.

Schaefer, K., A. S. Denning, and O. Leonard, 2005. The winter Arctic Oscillation, the timing of spring, and carbon fluxes in the northern hemisphere. *Global Biogeochemical Cycles,* **19**, GB3017, doi:10.1029/2004GB002336.

Sellers, P. J., Y. Mintz, Y. C. Sud, and A. Dalcher, 1986: A simple biosphere model (SiB) for use within general circulation models. *J. Atmos. Sci*., **43**, 505-531.

Sellers, P.J. et al,, 1996*a*: A Revised Land-Surface Parameterization (SiB2) for Atmospheric GCMs. Part 1: Model formulation. *J. Clim*., **9**, 676-705.

Sellers, P. J. et al,, 1996*b*: A Revised Land-Surface Parameterization (SiB2) for Atmospheric GCMs. Part 2: The generation of global fields of terrestrial biophysical parameters from satellite data. *J. Clim*., **9**, 706-737.

Suits, N.S., A.S. Denning, J.A. Berry, C.J. Still, J.Kaduk and J.B. Miller, 2005. Simulation of carbon isotope discrimination of the terrestrial biosphere. *Global Biogeochemical Cycles,* **19**, GB1017, doi:10.1029/2003GB002141.

Vidale, P.-L. and R. Stöckli, 2005. Prognostic canopy air space solutions for land surface exchanges. *Theor. And Appl. Climamtol*., **80**, 245-257. DOI: 10.1007/s00704-004-0103-2

Walko, R.L., C.J. Tremback, R.A. Pielke, and W.R. Cotton,1995: An interactive nesting algorithm for stretched grids and variable nesting ratios. *J. Appl. Meteor*., **34**, 994-999.

Wang, J.-W., 2005. *Observations And Simulations of Synoptic, Regional, and Local Variations of Atmospheric* CO_2 M. S. Thesis. Colorado State University, 146 pp.

Wofsy, S.C. and R.C. Harriss (2002), *The North American Carbon Program* (NACP). Report of the NACP Committee of the U.S. Interagency Carbon Cycle Science Program, US Global Change Research Program, Washington, DC.